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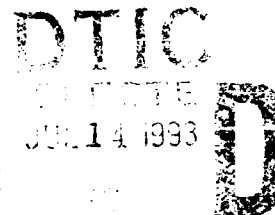
On Lidar signals induced by spatial variability of the
atmospheric refractive index

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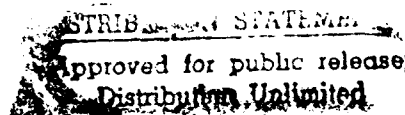
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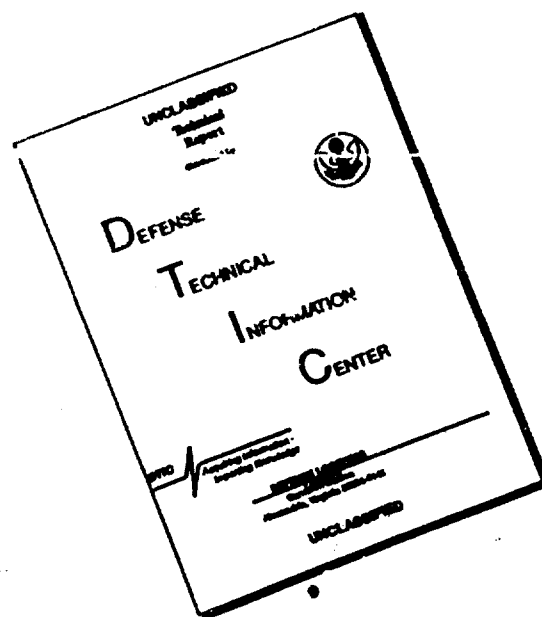
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ABSTRACT (ONGERUBRICEERD)

It is generally assumed that the intensity and the variation of lidar signals are caused by reflection of laser light by atmospheric aerosols of which concentration and size distributions are spatially inhomogeneous. However, lidar signals with strong variations are sometimes also detected during periods with low aerosol concentrations. It will be shown in this report that these variations might also be caused by spatial inhomogeneities of the atmospheric refractive index, which in turn are determined by variations in the atmospheric temperature, pressure and humidity. Furthermore, it is shown that the amount of reflection from turbulence cells can also be derived from the refractive index structure parameter, C_n^2 .

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SAMENVATTING (ONGERUBRICEERD)

Algemeen wordt aangenomen dat de sterkte en de variatie van lidarsignalen worden bepaald door de reflectie van laserstraling aan atmosferische aerosolen, waarvan de concentratie en de grootte-verdeling ruimtelijk inhomogeen kunnen zijn. Gebleken is echter dat ook tijdens perioden met weinig aerosol (zeer goed zicht) er soms sterke signalen met veel variaties worden gedetecteerd. In dit beknopte rapport wordt in het kort besproken dat dit mogelijk wordt veroorzaakt door ruimtelijke variatie van de atmosferische brekingsindex die bepaald is door de variatie in temperatuur, druk en vochtigheid van de lucht. Eveneens wordt aangetoond dat de mate van reflectie van turbulentie cellen afgeleid kan worden uit de structuurparameter van de brekingsindex, C_n^2 .

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1 INTRODUCTION

Lidar or laser radar is a generally accepted tool for remote sensing of some atmospheric parameters over ranges of several kilometers. The principle of lidar is based on the reflection of the laser light by atmospheric aerosols and molecules. Typical examples of atmospheric quantities which can be measured nowadays with different types of lidar systems are the visibility, the vertical structure of the extinction, the concentration of typical gases and the wind vector. See e.g. Measures, 1984. The lidar can also be used as a laser range finder or as an active imaging system by scanning a target. See e.g. Jelalian, 1992.

In a well mixed atmosphere, lidar signals show no spatial variation and the strength and the shape of the signals are a measure for the actual extinction and backscatter coefficients. On the other hand, if the lidar is operated in an inhomogeneous atmosphere the shape of the signals becomes complex and inversion of the extinction and/or backscatter coefficient as a function of range is complicated if not impossible. However, at the TNO Physics and Electronics Laboratory we sometimes observe rather strong signals with much spatial variations, although the atmosphere is very clear. Because it is assumed that the aerosol concentration is very low under those situations, there must be another atmospheric effect which causes these phenomena. In general, it is assumed that the variability of lidar signals is only caused by variations in the spatial aerosol concentration and/or size distribution. See e.g. Russell, Uthe and Ludwig 1974, Kunkel, Eloranta and Shiply 1977, Sasano et al 1982 and McElroy & Smith, 1986. However, it is noted that electromagnetic radiation can also be reflected at the interface between two materials with a different index of refraction. This effect, the so called Fresnel reflection, can be observed in our daily life e.g. the reflection of light from a window pane, the turbulent reflections above a warm road or the mirages at the sea or in the desert. In contrary to lidar, clear air structures as measured with radar are ascribed to refractive index variations as shown by e.g. Hardy and Ottersten 1969, Hardy and Katz 1969, Konrad 1970 and Noonkester 1976.

The phenomena mentioned above lead to the idea that the strong variations in lidar signals during clear atmospheric conditions might be also caused by adjacent parcels of air with different index of refraction. This can be induced by temperature, pressure and/or humidity differences between the air parcels.

Some papers dealing with the influence of turbulence on the performance of (coherent) lidar have been published but no papers have been found in the literature, thus far, which ascribe the effect of lidar backscatter from air parcels with different refractive index or from turbulence cells. Clifford and Lading 1983 investigated theoretically the influence of turbulence on the performance of a lidar with a very narrow field of view focussed at a fixed range. A promising paper on backscatter induced by refractive index differences was published by Fastig and Cohen, 1988. However, only reflections from hard targets were considered. Turbulence effects are often considered by investigators in relation to imaging over long distances. The performance of those systems are adversely influenced by wavefront distortion. See e.g. Strohbehn, Wang and Speck 1975, Brookner 1977 and Murty 1984.

This report will briefly summarize the influence of the atmospheric temperature, humidity and pressure on the refractive index and will try to make a first step in estimating the strength of the reflected laser light from air parcels with a different refractive index. Although the refractive index structure parameter, C_n^2 , plays a crucial role in the statistical description of turbulence, this will only be used here to estimate the magnitude of the reflection.

In Chapter 2 of this report, an overview is presented of empirical equations, as found in literature, which describe the refractive index of air. The variability is discussed in Chapter 3 and in Chapter 4 the amount of reflected light from air parcels with different refractive index will be estimated. Chapter 5 will conclude this work.

2 ATMOSPHERIC REFRACTIVE INDEX

The refractive index of air is not constant but depends on the wavelength and varies with temperature, pressure and humidity. In many publications, however, one or two of these parameters are skipped and one is only interested in either the microwave region (see e.g. Brookner 1977 or Falcone 1985) or in the optical part of the electromagnetic spectrum. Some papers discuss only the variation as a function of the atmospheric condition (e.g. Konrad 1970) or give only the basic Lorenz-Lorentz equations to calculate the refractive index of a gas (e.g. Weichel 1989). Much referenced work on the determination of the refractive index of air has been done in the past (e.g. Kayser 1925, Barrel and Sears 1939 and Edlén 1953) and introduces a lot of confusion between the different units for temperature, pressure and especially for humidity. This has lead to different empirical equations which appear to be very close as shown by Edlén 1966 and Teillet 1990. However, these authors were only interested in the dispersion of standard dry air (15 °C, 1013.25 mBar, 78.09 % N₂, 20.95 % O₂, 0.93 % Ar and 0.03 % CO₂) in the optical part of the spectrum and thus skipped the dependence on temperature, humidity and pressure. Therefore their results cannot be used here. Some of the other empirical equations as published by several authors are summarized below.

If there is some uncertainty in the published definition of the unit or in the numerical value, the word '(error)' is placed behind the term. The units are copied as found in the original publications.

a. Index of refraction as published by Owens 1967

Owens reviewed the theoretical background and the knowledge of the refractive index of air up to 1967. The starting point for Owens was the Lorenz-Lorentz equation which was applied to standard dry air which is composed of 78.09 % N₂, 20.95 % O₂, 0.93 % Ar and 0.03 % CO₂ and has a temperature of 15 °C and a pressure of 1013.25 mBar. The contribution of each gas, including the water vapour, to the refractive index was calculated separately, which leads to the following equation with a dry and a wet part:

$$(n-1) \cdot 10^8 = \left[2371.34 + \frac{683,939.7}{130 - \sigma^2} + \frac{4547.3}{38.9 - \sigma^2} \right] \cdot D_s + \\ + \left[6487.31 + 58.058 \cdot \sigma^2 - 0.71150 \cdot \sigma^4 + 0.08851 \cdot \sigma^6 \right] \cdot D_w$$

where:

D_s and D_w are the so called density factors according to:

$$D_s = \frac{P_s}{T} \left[1 + P_s \cdot \left(57.90 \cdot 10^{-8} - \frac{9.3250 \cdot 10^{-4}}{T} + \frac{0.25844}{T^2} \right) \right]$$

and

$$D_w = \frac{P_w}{T} \left\{ 1 + P_w \cdot \left[1 + 3.7 \cdot 10^{-4} \cdot P_w \right] \right\} * \left[-2.37321 \cdot 10^{-3} + \frac{2.23366}{T} - \frac{710.792}{T^2} + \frac{7.754141 \cdot 10^4}{T^3} \right]$$

P_s = partial pressure of dry air in mBar

P_w = partial water vapour pressure in mBar

T = temperature in K

σ = wavenumber ($1/\lambda$) in μm^{-1}

Notes:

The unit of the wavenumber is not given by Owens but has been extracted from the article of Edlén 1966.

In contrast to other authors, Owens published his equation in terms of $(n-1) \cdot 10^8$ but the numerical results were presented in terms of $(n-1) \cdot 10^6$, the refractivity.

It seems that there is some confusion in the sign of the wet part of the refractivity between Owens' equation and the equations published by Fenn et al 1985 and Friehe 1975 (see below). This is caused by the meaning of the pressure term in the different equations. Owens used the partial pressures of the separate gases whereas the other authors uses the total pressure.

b. Index of refraction as published by Friehe et al 1975

Friehe, LaRue, Champagne, Gibson and Dreyer referred to the article of Barrell and Sears 1939 who split (as many others did) the equation for the refractivity N of air in a contribution of dry air and a contribution water vapour.

$$N = A(\lambda) \cdot \frac{P \{ 1 + (1.049 - 0.157 \cdot T) \cdot P \cdot 10^{-6} \}}{1 + T / 273.16} - B(\lambda) \cdot \frac{f}{1 + T / 273.16}$$

where:

$N = (n-1) \cdot 10^6$ = refractivity of air

n = refractive index of air

f = partial water vapour pressure in torr

P = total atmospheric pressure in mm Hg

T = temperature in °C

$$A(\lambda) = 0.378125 + 0.0021414/\lambda^2 + 0.00001794/\lambda^4$$

$$B(\lambda) = 0.0624 - 0.000680/\lambda^2$$

λ = wavelength in μm in vacuum

Note: The conversion from absolute humidity Q to partial water vapour pressure is:

$$f = Q \cdot (T + 273.16) / 289.2.$$

c. Index of refraction as published by Clifford 1978

Strohbehn published an equation for the refractive index and neglected the contribution of the water vapour.

$$(n-1) = 77.6 \cdot (1 + 7.52 \times 10^{-3} \lambda^{-2}) \cdot (P/T) \cdot 10^{-6}$$

where:

P = pressure in mBar
T = temperature in K
 λ = wavelength in μm

d. Index of refraction as published by Zuev 1982

Zuev published two equations for the refractive index of air. The first one includes temperature, humidity and pressure and has been copied from Kazanskii 1966. The second one was a copy and/or modification from the one published by Chamberlain 1961 in which the humidity contribution was omitted.

$$(n-1) = C_1 \cdot \frac{P}{T} \cdot \left(1 - 0.132 \cdot \frac{e}{P} \right)$$

where:

C_1 = wavelength dependent factor; for $\lambda \approx 0.6 \mu\text{m}$, $C_1 = 1.0485 \cdot 10^{-4}$
P = pressure in mm Hg
e = absolute humidity in mm Hg (error)
T = temperature in K

The second equation for the refractive index was copied and/or modified from the results of Chamberlain 1961.

$$N = \left(103.38 + \frac{0.5854}{\lambda^4} \right) \cdot \frac{P}{T}$$

where:

N = refractivity = $(n-1) \cdot 10^6$: (error; 10^{-6} should probably be 10^6)
 λ = wavelength in μm
P = pressure in mm Hg
T = temperature in K or $^{\circ}\text{C}$

e. Index of refraction as published in the Handbook of Geophysics and Space Environment 1985 (Fenn and Falcone)

e1. According to Fenn

Fenn, 1985, published the results for the refractivity from Edlén 1966 who split the refractivity in a dry part and a wet part.

$$N = \left[a_0 + \frac{a_1}{1 - (v / b_1)^2} + \frac{a_2}{1 - (v / b_2)^2} \right] \cdot \frac{P}{P_0} \cdot \frac{(T_0 + 15.0)}{T} - \left[c_0 - (v / c_1)^2 \right] \cdot \frac{P_w}{P_0}$$

where:

$$a_0 = 83.42$$

$$a_1 = 185.08$$

$$a_2 = 4.11$$

$$b_1 = 1.140 \cdot 10^5$$

$$b_2 = 6.24 \cdot 10^4$$

$$c_0 = 43.49$$

$$c_1 = 1.70 \cdot 10^4$$

$$P = \text{air pressure in mBar}$$

$$P_0 = 1013.25 \text{ mBar}$$

$$T = \text{temperature in Kelvin}$$

$$T_0 = 273.15$$

$$P_w = \text{partial water vapour pressure in mBar}$$

$$v = 10^4 / \lambda = \text{frequency in cm}^{-1}$$

$$\lambda = \text{wavelength in } \mu\text{m}$$

e2. According to Falcone

Falcone, 1985, published a formula for the refractivity for the wavelength interval 0.2 .. 20 μm :

$$N = \frac{77.6 \cdot P}{T} + \frac{0.584 \cdot P}{T \cdot \lambda^2}$$

where:

P = atmospheric pressure in mBar

T = atmospheric temperature in Kelvin

λ = wavelength in μm

f. Index of refraction as published by Sadot and Kopeika 1992

Sadot and Kopeika referred to five different papers in the period 1969 to 1985 and resumed the following equation for the index of refraction:

$$N = \frac{77.6 \cdot P}{T} \left(1 + \frac{0.00753}{\lambda^2} - 7733 \cdot \frac{q}{T} \right) \cdot 10^{-6}$$

where:

n = refractive index structure parameter (error)

P = pressure in mBar

T = temperature in K

λ = wavelength in μm

q = specific humidity in gr/m^3 (error)

Some remarks at this point:

The 'dry' part of the refractivity as published by Falcone and by Sadot and Kopeika are equal but the constant of 77.6 is normally found in connection with the refractive index in the RF and microwave part of the spectrum (e.g. Brockner 1977 and Beaulieu 1992). The equations published by Strohbehn, Falcone and Zuev do not include any humidity term and are therefore not

further considered here. Also note that there must be an error in the first equation of Zuev because the absolute humidity is measured in gr/m^3 instead of mm Hg. (Specific humidity is expressed in the ratio of the units mass/mass, e.g. gr/kg ; see e.g. Lowry 1970.) However, if his unit gr/m^3 is correct, then the term 'absolute humidity' should be replaced by 'partial water pressure'. Also note that the factor 10^{-6} should be 10^6 . Because of these uncertainties, this reference is also skipped. Sadot and Kopeika were somewhat careless in both the description of the refractivity and in the published equation. The authors defined the index of refraction as 'refractive index structure parameter' and expressed the atmospheric water content as 'specific humidity' in the unit gr/m^3 . If this unit is correct then the quantity should be 'absolute humidity'. The quantity 'specific humidity' has no dimension (mass/mass). Furthermore, if his expression was for the refractive index then the factor 10^{-6} should probably be 10^6 and a value of one should be added to the results. Finally, the wet part of the equation has a T^{-2} dependence, which is not given by Fenn and by Friehe. Because of these uncertainties, the equation of Sadot will not be used.

The independent results from Owens 1967 (re-calculated from the basic Lorenz-Lorentz equation and basic data from other authors), Friehe et al 1975 (based on the work of both Barell and Sears 1939) and from Fenn et al 1985 (based on the work of Edlén 1966) have been adopted for further calculations for the variations in the refractivity caused by temperature, humidity and pressure. Numerical calculations show that the refractivity of both the 'dry' and the 'wet' part from different authors are within 1 %.

3 VARIABILITY OF THE REFRACTIVE INDEX

Equations have been summarized in the previous chapter for the refractive index of the air in terms of wavelength, atmospheric temperature, humidity and pressure. Different empirical equations have been found in the literature for the optical part of the spectrum and for the microwave region. In this section we will only concentrate on the optical part of the spectrum. To calculate the reflectivity from a boundary between two adjacent air parcels with different index of refraction, it is sufficient to determine the variation of the refractive index with temperature, humidity and pressure at the wavelength of interest. The formal way to reach this goal is to determine the derivative of the empirical equations with respect to the atmospheric parameters. In practice, however, the variations of temperature, humidity and pressure are small under normal atmospheric conditions as shown by Friehe et al 1975. Therefore the derivative has been calculated numerically for a reasonable atmospheric condition and its variation.

Friehe et al 1975 noted that above the sea the temperature between turbulence cells may vary by about 0.3 degrees Celsius, the humidity by about 0.5 gr/m³ and the pressure by about 3.10⁻³ mBar. The variation of the refractive index at 1.06 μm and at a fixed atmospheric condition is shown in Table 3.1

Table 3.1: Variation in the atmospheric refractivity N according to Owens 1967, Friehe et al 1975 and Fenn et al 1985 at a wavelength of 1.06 μm. Atmospheric condition: 293 K, 1000 mBar (total pressure) and 10 g/m³. The variations in these parameters are respectively 0.3 K, 3.10⁻³ mBar and 0.5 gr/m³.

	Owens	Friehe	Fenn	
dN _P	7.98.10 ⁻⁴	7.97.10 ⁻⁴	7.97.10 ⁻⁴	(dP=3.10 ⁻³ mBar)
dN _T	-2.72.10 ⁻¹	-2.80.10 ⁻¹	-2.72.10 ⁻¹	(dT=0.3 K)
dN _Q	-2.87.10 ⁻²	-2.92.10 ⁻²	-2.88.10 ⁻²	(dQ= 0.5gr/m ³)

Remarks:

- The variation of refractivity N, as calculated with different equations are in good agreement.

- The results from Table 3.1 compare well with the results obtained with equation (16) of Friehe et al 1975

$$(dN = 0.366 \cdot dP - 1.00 \cdot dT - 0.05667 \cdot dQ).$$

- At the given variations of the atmospheric parameters, the temperature has the largest impact on the reflectivity.
- Pressure variations disperse quickly and have less influence on the variation of the refractive index (Weichel 1989).

If all the variations have equal sign than the maximum variation in the refractive index n , amounts in this case about $dn \approx 0.3 \cdot 10^{-6}$.

At this moment, no information is available on the temperature, humidity and pressure variations over land, but it is expected that the temperature variations are larger and so the variation in refractive index.

In view of numerous publications on turbulence, it is also possible to estimate the difference in refractive index from the refractive index structure parameter C_n^2 which has been defined as:

$$C_n^2 = \langle (n_1 - n_2)^2 \rangle r^{-2/3},$$

where:

- n_1 = refractive index at position r_1
- n_2 = refractive index at position r_2
- r = distance between r_2 and r_1

Values for the C_n^2 structure parameter have been published a.o. by Wesely and Alcarez 1973, Weichel 1990 and Sadot and Kopeika 1992 and varies from 10^{-17} for a normal atmosphere to 10^{-12} for strong turbulence.

If the difference in refractive index dn is calculated between two points separated by 1 meter, the expression for the structure parameter becomes:

$$C_n^2 \mid_{r=1} = \langle (dn)^2 \rangle$$

This is the averaged value of C_n^2 . Assuming that actual values can be 3 times or more larger than this averaged value, gives values for dn^2 on the order of $3 \cdot 10^{-17} \dots 3 \cdot 10^{-12}$. As a result, the reflectivity $R = \{(n_1 - n_2)/(n_1 + n_2)\}^2$ becomes about $2.0 \cdot 10^{-18} \dots 2.0 \cdot 10^{-13}$. This range includes the order of the magnitude of the value of $(0.3 \cdot 10^{-6})^2$ found from our estimate given above

4 ESTIMATION OF THE REFLECTED LIGHT

To estimate the amount of light reflected by the boundary of two air parcels, Fresnel reflection equation is used (ideal approximation):

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2} \right]^2 \approx \left[\frac{dn}{2} \right]^2 = \frac{dn^2}{4}$$

Substitution of the variation in the refractive index dn of $0.3 \cdot 10^{-6}$, as shown in the previous chapter, provides a reflectivity of about:

$$R \approx 2.3 \cdot 10^{-14}.$$

Reflected power of such a boundary

The pulse peak power of the 'SMAL' laser is about 1 MW and the receiver sensitivity is about 10^{-9} W. For the reflectivity, R , found above, the reflected pulse power from a single boundary step is about $2.3 \cdot 10^{-8}$ W. This is about a factor 23 stronger than the minimum detectable power of the receiver.

In practice, the size of the cells may vary from a few cm to hundreds of meters and more as shown by Konrad 1970 and Wiechel 1989. This means that more than one boundary can be present within one laser pulse length and that the reflected power will be the summation of the individual reflections. If this is the case, a relatively strong signal will be generated in the receiver dependent on the number of boundaries and the magnitude of the refractive index difference. On the other hand, if the distance between the boundaries of the different air parcels is larger than the length of the laser pulse, those boundaries will generate a train of pulses or a modulation of the received signal.

5 CONCLUSION

The difference in the refractive index of two neighbouring volumes of air, caused by different temperature, humidity and pressure, may be large enough to produce amplitude variations of lidar return signals. An estimate of the refractive index difference between eddies, calculated from the structure parameter, also points in this direction. The variations of the value of atmospheric parameters, as found in literature, show that temperature variations have the largest impact on the refractive index.

It is assumed that the reflection is specular. In practice, however, this will not be the case. This means that the reflected light will also be scattered in other directions, but there is no indication on the shape of the boundary of the air parcels and thus on the scatter diagram.

In view of this result it becomes very difficult, if not impossible, to discriminate between scattering by aerosols and by the boundary of atmospheric parcels with different refractive index.

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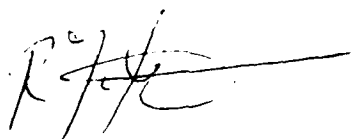
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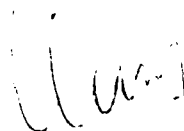
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APPENDIX A: USEFUL EQUATIONS

1. The relative humidity expressed in the dew point temperature T_{DP} (K) and the ambient temperature T_A (K) (Bissonnette 1990):

$$RH(\%) = 100 \cdot \exp \left\{ (17.2694) \cdot \left[\frac{T_{DP}}{T_{DP} + 283.3} - \frac{T_A}{T_A + 283.3} \right] \right\}$$

2. The relative humidity expressed in the dew point temperature T_d (K) and the ambient temperature T_a (K) (Brookner 1977)

$$RH = \left[\frac{T}{T_d} \right]^2 \cdot \exp \left\{ \left[\frac{T_d - 273}{3.5} + 2.3 \right]^{0.5} - \left[\frac{T - 273}{3.5} + 2.3 \right]^{0.5} \right\}$$

3. The absolute humidity Q (gr/m^3) expressed in the partial water vapour pressure f (mm Hg) and the ambient temperature T_a (K) (Friehe 1975).

$$Q = 2.892 \cdot 10^2 \cdot \frac{f}{T_a}$$

4. Absolute humidity Q (gr/m^3) expressed in partial water vapour pressure and the temperature (Owens 1967).

$$Q = 216.582 \cdot (P/T) \cdot [1 + P \cdot \beta(P) \cdot \gamma(T)]$$

Where:

$$\beta(P) = 1 + (3.7 \cdot 10^{-4}) \cdot P$$

$$\gamma(T) = -2.37321 \cdot 10^{-3} + \frac{2.23366}{T} - \frac{710.792}{T^2} + \frac{7.75141 \cdot 10^4}{T^3}$$

5. Saturation water vapour pressure P_s (mBar) expressed in the ambient temperature T (K) (Owens 1967).

$$\begin{aligned} {}^{10}\log(P_s / P_o) = & 10.79586 \cdot (1 - T_o / T) - 5.02808 \cdot \log(T / T_o) + \\ & + 1.50474 \cdot 10^{-4} \cdot \left[1 - 10^{-8.29692(T/T_o - 1)} \right] + \\ & + 0.42873 \cdot 10^{-3} \cdot \left[10^{4.76955(1 - T_o/T)} - 1 \right] - \\ & - 2.2195983 \end{aligned}$$

Where:

P_o = standard atmospheric pressure, 1013.25 mBar

P_s = saturation water vapour pressure in mBar

T = ambient temperature in K

T_o = absolute temperature, 273.16 K

6. Absolute humidity, expressed in relative humidity and ambient temperature. (Rouault and Mestayer, private communication, 1989)

$$Q = q_1 \cdot \frac{RH}{100}$$

with:

$$q_1 = \frac{\rho_a \cdot 0.622 \cdot e_i}{(P - 0.378 \cdot e_i)}$$

$$e_i = 6.1078 \cdot e^{\left(\frac{17.27 T}{T + 237.3} \right)}$$

where

T = ambient temperature in °C

P = pressure in mBar

Q = absolute humidity in gr/gr

RH = relative humidity in %

ρ_a = density of air (1.2)

7. Saturated water vapour pressure, saturated and absolute humidity, expressed in ambient temperature and pressure.

(Bolton, Monthly Weather Review, 1980, vol. 108)

$$P_s = 6.112 \cdot e^{\frac{17.67 \cdot T_a}{T_a + 243.5}}$$

$$Q_s = \frac{622 \cdot P_s}{(P - P_s)}$$

$$Q = \frac{Q_s \cdot RH}{100}$$

where:

P = ambient pressure in mBar

P_s = saturated water vapour pressure in mBar

Q = absolute humidity in gr/kg

Q_s = saturated absolute humidity in mBar

RH = relative humidity in %

T_a = ambient temperature in °C

8. Saturated water vapour pressure and absolute humidity expressed in ambient temperature and pressure (Andreas 1989)

$$P_s = (1.0007 + 3.46 \cdot 10^{-6} \cdot P) \cdot 6.1121 \cdot e^{\frac{17.502T}{240.97+T}}$$

$$Q = \frac{100 \cdot M_w \cdot P_s \cdot RH}{R \cdot T_a}$$

where

M_w = molecular mass of water, 18.01

P = ambient pressure in hPa

P_s = saturated water vapour pressure in hPa

Q = absolute humidity in g/m^3

R = universal gas constant, $8.3143 \cdot 10^3$ J/deg

RH = relative humidity (-)

T = ambient temperature in $^{\circ}C$

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